Chapter 4
Passive Cooling of Buildings: Present and Future Needs: Recent Progress on Passive Cooling Convective Technologies

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Abstract The maximisation of energy efficiency in buildings can be performed by successful demonstration of the passive technologies. Passive cooling is passing to a phase of maturity, while significant research has been performed worldwide. The aim of this chapter is to underline and review the recent state-of-the-art technologies for passive cooling convective strategies for buildings and their contribution in the improvement of the indoor environmental quality as well as in the reduction of cooling needs. The paper starts with a short introduction in passive cooling needs and continues with the analysis of the two passive cooling convective techniques, i.e. ground cooling and night ventilation.

Keywords Passive cooling • Ground cooling • Ventilative cooling

4.1 Introduction

The building sector represents the most important consumer of energy with an average share close to 40 %. While in the developed world heating seems to be the more consuming of the specific building energy needs, cooling is a very intensive energy activity presenting a continuously increasing share in the overall energy budget of the buildings sector. In fact, the energy consumption for cooling purposes increases almost everywhere in the world because of the improved standards of life, the relative affordability of air-conditioning systems in the developed world, the inappropriateness of buildings to avoid indoor overheating due to the adoption of design standards proposed by a rather universal modern architecture, and, the most important, because of the serious temperature increase in the urban environments (Antinucci et al. 1992).

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Global climatic change and heat island increase urban temperatures and extreme heat-related climatic phenomena. The ambient temperature of numerous urban locations has increased considerably in the last years because of the heat island phenomenon. Heat island relies on higher urban temperatures compared to the suburban or rural ones because of the positive thermal balance of cities. Important research carried has permitted to fully document the intensity of heat island in Europe and the other continents (Santamouris 2007).

Several studies have shown the relation between heat island and the excess need for cooling. Higher urban temperatures increase the absolute energy consumption of the buildings during the summer period and raise the peak electricity demand (Akbari et al. 1992; Cartalis et al. 2001; Hassid et al. 2000; Santamouris et al. 2001). In parallel, the heat island phenomenon intensifies the stress in urban areas (Pantavou et al. 2011), increases pollution in cities as higher urban temperatures, accelerates the rate of photochemical ozone production (Stathopoulou et al. 2008), and expands the ecological footprint of the cities (Santamouris et al. 2007b).

Apart from the heat island phenomenon, the global climatic change observed not only in urban areas has a serious impact on the energy consumption of buildings for cooling purposes. Cooling degree days are considerably increased during the last years in most zones of the planet, while the future cooling energy demand seems to be much higher than some decades ago. For example, an analysis of 40 years of hourly data series from nine meteorological stations in Greece performed to understand the impact of air temperature, and relative humidity trends on the energy consumption of buildings has shown that for the period in question, the heating load in the Greek building sector has decreased by about 1 kWh/m^2 per decade, while the cooling load increased by about 5 kWh/m^2 per decade (Kapsomenakis et al. 2013). In parallel, many studies examined the relation of future temperatures with the cooling energy needs of buildings. All studies have shown that very important energy consumption has to be expected unless severe technological measures are taken. In particular, recent research has shown that because of the expected serious future temperature increase, the heating energy demand of the building sector in Greece could decrease by about 50 %, while the corresponding energy consumption for cooling could increase by 248 % until 2100 (Asimakopoulos et al. 2012).

High ambient temperatures have a serious impact on the quality of life of the general population but mainly on the so-called low-income or vulnerable population. It is well known that low-income population has to spend more energy than high-income people, to satisfy the specific cooling and heating demands per square metre because of the inferior quality of the building envelope and lower energy performance of the houses they are living in. It is characteristic that the low-income population in Greece has to spend almost 120 % more per square metre and inhabitant than the high-income group to satisfy the specific cooling needs of the houses (Santamouris et al. 2007a).

The problem is quite dramatic for the vulnerable and low-income population that cannot afford to pay for air-conditioning. Measurements performed in Athens during the heat waves of 2007 in some tenths of low-income houses have shown that the inhabitants lived in temperatures above 34 °C for more than 200 continuous hours (Sakka et al. 2012). The specific indoor conditions put a serious threat to the health of low-income citizens and increase highly the mortality rates.

Passive cooling systems and in particular technologies based on convective heat amortisation systems have achieved a very high degree of development (Santamouris and Kolokotsa 2013). The new proposed technologies have proven very efficient and when used may improve the indoor environmental quality and decrease the energy cost of buildings. As mentioned by Santamouris et al. (2007c), the new proposed and developed technologies are characterised by low cost and are easy to apply.

The present article investigates the present and future needs for cooling while it tries to present the more promising new developments on the field of convective heat amortisation techniques.

4.2 Present and Future Needs for Cooling

As mentioned in the previous sections, the important climate change and heat island phenomenon have increased considerably the cooling load of buildings. Several studies are performed to investigate the impact of heat island on the cooling needs of buildings.

Studies in the USA have shown that in cities with population larger than 100,000 citizens, the electricity load increases by 1.5–2 % for every degree F of temperature increase (Akbari et al. 1992). Given that the temperature increase in some US cities during the summer afternoons is between 2 and 4 °F, it is calculated that 3–8 % of the current demand of electricity in the urban areas is used to compensate the heat island phenomenon. In parallel, in Los Angeles, USA, it is found that the net rate of increase of the electricity demand is close to 300 MW per degree F. It is also estimated that the absolute temperature increase in the city since 1940 is 5 F, which is translated to an additional electricity demand of 1.5 GW attributed fully to the heat island phenomenon. Akbari has calculated that in the USA the electricity costs to compensate heat islands could be as much as 1 million dollars per hour or almost 1 billion dollars per year (Akbari et al. 1992).

In Athens, Greece, the spatial distribution of the cooling load of a typical building is calculated using temperature data from a very high number of temperature stations. Figure 4.1 gives the iso-cooling lines in kWh/m^2 and month. As shown, the necessary cooling load at the centre of the city is almost double than in the suburban areas. Much higher values are calculated in zones of high density and high anthropogenic heat generated (Santamouris et al. 2001).

Apart from increased energy loads for cooling, high ambient temperatures increase the peak electricity loads and put a serious strength on the local utilities. It is calculated that the peak cooling demand in Athens, present a very high increase because of the heat island phenomenon. In particular, while the peak demand for a typical office in the suburban zones of Athens is close to 13.7 kW, the corresponding load at the centre of the city is 27.5 kW.

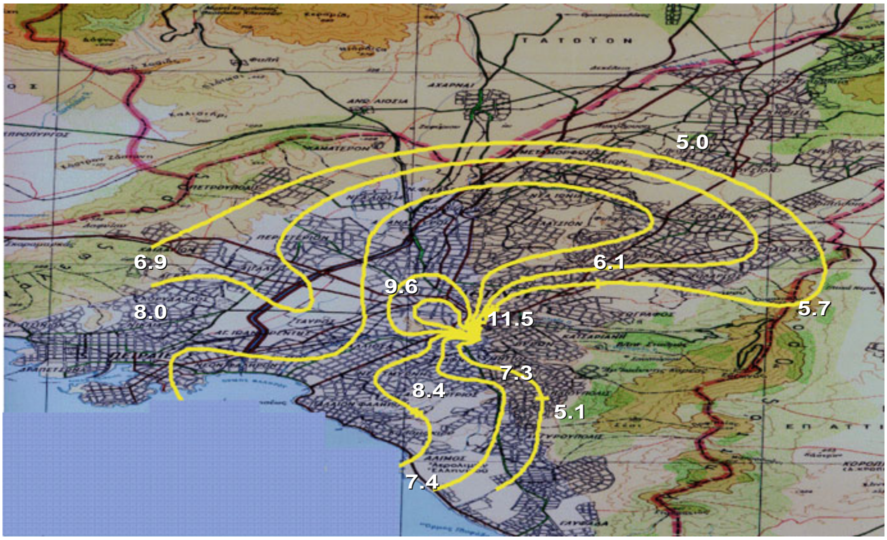

Fig. 4.1 Distribution of the cooling load in the city of Athens for a set point temperature of 27 °C and for August 1996

The impact of climate change on the ambient temperature is already very important, and it is expected to further increase if additional mitigation and adaptation measures are not taken. Forty years of ambient temperature have been used to calculate the evolution of cooling and heating loads in typical buildings for various cities in Greece (Kapsomenakis et al. 2013). Data covered the period 1970–2010. The calculated increase of the cooling load is shown for four major cities in Fig. 4.2. As shown, the cooling energy demands have increased seriously in the last 40 years, and the corresponding increase rate is close to 5 kWh/m^2 per decade. A further analysis for the same zone of Europe has attempted to identify the future energy needs of buildings considering the various scenarios proposed by IPCC regarding the evolution of the ambient temperature (Asimakopoulos et al. 2012). It is found that the expected increase of the cooling needs for a residential building considering the A1B scenario for 2041–2050 will be 83 % compared to the actual situation and 167 % for the period 2091–2100. The results are given in Fig. 4.3 for three types of residential buildings: a building constructed using technology of 1980, a contemporary building and a passive house. It is evident that because of the important temperature increase, cooling loads will skyrocket unless appropriate mitigation and adaptation techniques are considered.

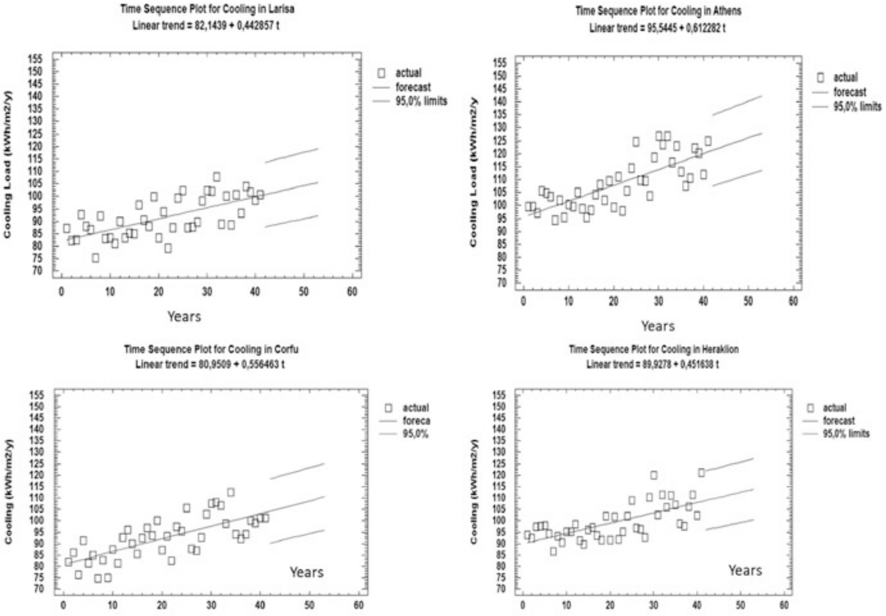

Fig. 4.2 Annual variation of the cooling load in four major Greek cities (Kapsomenakis et al. 2013)

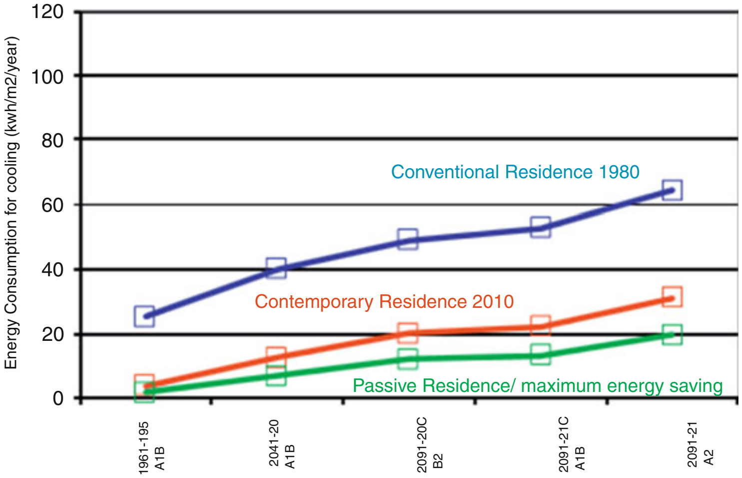

Fig. 4.3 Change of the energy consumption for cooling of a conventional (*black*), a contemporary (*red*) and a passive (*green*) residence in Attica for all climatic scenarios (Asimakopoulos et al. 2012)

4.3 Passive Cooling to Fight Vulnerability and Protect Low-Income Population

High urban temperatures have a very serious impact on the health of urban population. High ambient temperatures are found to cause important cardiovascular, respiratory and cerebrovascular disorders (McMichael et al. 1996). In parallel, high ambient temperatures decrease the viscosity of the blood and increase the risk of thrombosis, while older residents have problems of thermoregulation and impaired kidney function. Various studies investigating the relation of the ambient temperature against hospital admissions have shown that during warm periods, the number of admissions increases for conventional heat-related diseases like heat stroke, heat exhaustion, neurological conditions mental illness and renal diseases (Kovats et al. 2004).

Exposure of human beings in extreme high temperatures may result in increased human losses. Analysis of the impact of the last decade heat waves has shown that mortality increases highly, while most of the victims belong to the low-income and vulnerable groups. Baccini et al. (2008) examined the impact of high temperatures on excess mortality for 15 European cities and reported that the threshold for Mediterranean cities is close to 29.4 °C while it is much lower 23.3 °C for Northern and Condimental cities. As reported, increase of the temperature by 1 C above the threshold increases mortality by 3.12 % in the Mediterranean and 1.84 % in Northern Europe. Figure 4.4 reports in a comparative way the transfer functions

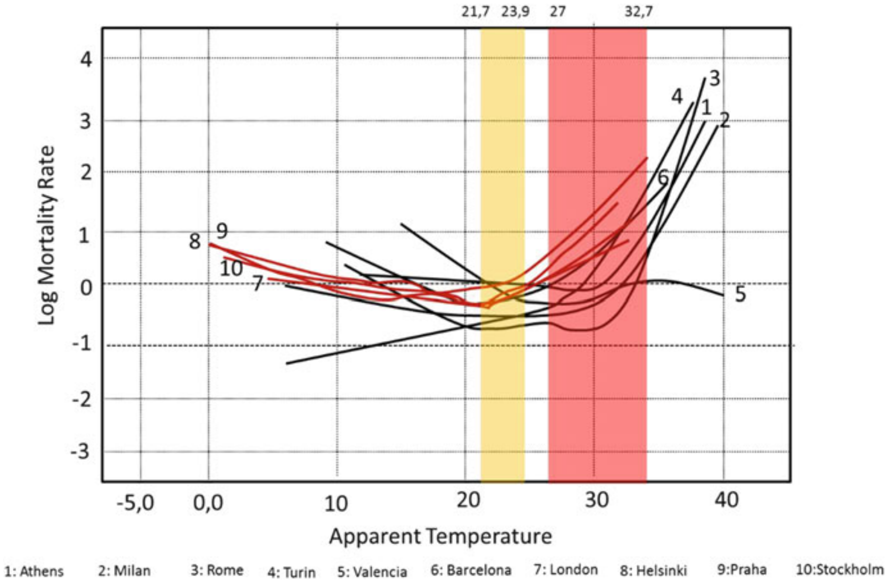

Fig. 4.4 Transfer functions between ambient temperature and the Log of Mortality Rate as reported by Baccini et al. (2008). Also, the specific bands for the Mediterranean and Northern countries where mortality starts to rise are given

between the ambient temperature and the log of the mortality for some Mediterranean and Northern cities as reported by Baccini et al. (2008).

The use of advanced passive cooling techniques may provide a very reliable solution to avoid health problems and decrease mortality during heat waves. The use of heat dissipation techniques like natural and nighttime as well as the use of low-cost evaporative and ground systems may improve the environmental quality of vulnerable population and save lives.

4.4 Recent Progress on Convective Passive Cooling Techniques

4.4.1 Ventilative Passive Cooling

It is widely known that the oldest, straightforward convective passive cooling method admits cool night air to drive out the warm air. Nocturnal convective cooling exploits the cold night air to cool down the building's absorbed heat gains during daytime and reduce the daytime temperature rise. Night ventilation can either be driven by natural forces – i.e. stack or wind pressure difference – or may be sometimes supported by a small fan power to provide sufficient airflow at times when the natural forces are weak. As a consequence, temperature peaks are reduced or even postponed. For specific climatic conditions, the cooling potential of night ventilation techniques depends on the air flow rate, the thermal capacity of the building, and the appropriate coupling of the thermal mass and the air flow. As a result, the effectiveness of night ventilation techniques is determined by the prevailing climatic conditions, the microclimate, the building characteristics and the location (Geros et al. 2005; Santamouris et al. 1996). The outdoor temperature, the relative humidity and the wind speed are the environmental parameters that influence the successful application of night ventilation techniques. Other parameters (Kolokotroni and Aronis 1999) can be the building mass, glazing ratio, solar and internal gains and orientation.

To better understand the relative phenomena and also quantify the impact of convective nocturnal ventilation techniques, important experimental and theoretical research has been carried out (Santamouris et al. 2010).

Santamouris et al. (2010) pointed out that the application of night ventilation techniques to residential buildings may lead to a decrease of cooling loads almost 40 kWh/m^2/y with an average contribution of 12 kWh/m^2/y. In urban areas though, the urban heat island (UHI) phenomenon deteriorates quality of life and has a direct impact on the energy demand, the environmental conditions and, consequently, ventilation effectiveness. The increased urban temperatures (Livada et al. 2002, 2007) exacerbate the cooling load of buildings, increase the peak electricity demand for cooling, decrease the efficiency of air-conditioners (Cartalis et al. 2001; Santamouris et al. 2001) and create an emerge necessity for passive cooling.

Specific monitoring studies in real buildings or test cells are reported in Allard and Santamouris (1998), Blondeau et al. (1997), Geros et al. (1999, 2005), Givoni (1994), Kolokotroni et al. (1997), Krüger et al. (2010), Kubota et al. (2009), Pfafferott et al. (2003), Santamouris and Assimakopoulos (1997), Springer et al. (2005), van der Maas and Roulet (1991) and Zimmerman and Andersson (1998). Most of the studies conclude that the use of convective ventilation in free-floating buildings may decrease the next day peak indoor temperature up to 3 K. In parallel, when applied in air-conditioned buildings, a considerable reduction of the peak cooling may be expected.

Available design methods for night ventilation range from simple analytical and empirical methods to multi-zone and computational fluid dynamics (CFD) techniques (Jiru and Bitsuamlak 2010; Li and Nielsen 2011; Li and Heiselberg 2002).

Most analytical approaches are based on a conventional macroscopic approach that utilises the Bernoulli equation for flow and opening (Allard and Santamouris 1998). This equation, which is based on the conservation of energy, is used to calculate air velocities through openings.

Network models are widely used for simulation of ventilation in multi-zone buildings coupled with thermal flow analysis (Li and Heiselberg 2002). The network method is based on the application of the Bernoulli equation to determine the pressure difference and hence flow rate across each opening in the flow network (Flourentzou et al. 1998). Zones are interconnected by flow paths, such as cracks, windows, doors and shafts, to form a flow network. Network methods are able to take into account the effects of outdoor climate, the location and size of each opening, and stack, wind and mechanically driven ventilation.

Computational fluid dynamics are based on the Navier-Stokes equations. CFD simulation provides detailed distribution of air temperature, air velocity, contaminant concentration within the building and its surrounding areas. However, the application of CFD for convective cooling prediction has been limited due to increased computational time and computer requirements. Building simulation tools facilitate energy-efficient, sustainable building design by providing rapid prediction of thermal comfort, indoor air flow of the building and better understanding of the consequences of ventilation for cooling. Another modelling software that is very frequently used is TRNSYS coupled with COMIS (Duffy et al. 2009; Fiksel et al. 1995). The specific technique is a combination of thermal modelling with air flow representation and is a very powerful tool for estimating thermal comfort coupled with indoor air quality (Fraisse et al. 2010; Manz and Frank 2005).

Moreover convective cooling via ventilation is a suitable technique for various building types including offices, residential, industrial, etc. Some examples are included below:

- Concerning office buildings, a significant number of studies are showing the ventilative cooling effectiveness. Blondeau et al. (1997) studied the night ventilation in offices during summer period, showing a reduction of diurnal variation from 1.5 to 2 K. Kolokotroni et al. (Kolokotroni et al. 1998; Kolokotroni 2001) showed that the energy savings for night ventilation in UK offices can be about 5 %.

- For residential buildings, various studies can be found. For example, the effectiveness of night ventilation technique for residential buildings in hot-humid climate of Malaysia is analysed in Kubota et al. (2009). The effects of different natural ventilation strategies on indoor thermal environment for Malaysian terraced houses are evaluated based on the results of a full-scale field experiment. The results indicated that the cooling effect of night ventilation is larger than those of the other ventilation strategies during the day and night. Night ventilation with solar chimneys is applied to social housing design for hot climates in Madrid (Macias et al. 2006). Storage chimneys – oriented to the west – collect solar gains during the afternoon, while the surface temperatures of the concrete walls reach temperatures up to 50 °C. The fresh cold night air enters through the east facade and runs through the flat, cooling down the thermal masses of the open walls and ceilings. Results of the simulation show that indoor temperature remains between 21 °C and 23 °C during the night. Two hundred and fourteen air-conditioned residential buildings using night ventilation techniques have been analysed in Santamouris et al. (2010). It has been found that night ventilation applied to residential buildings may decrease the cooling load up to 40 kWh/m^2 per year with an average contribution close to twelve, 12 kWh/m^2 per year .
- Night ventilation coupled with double skin facades for industrial archaeology buildings is studied in Ballestini et al. (2005) showing using simulation techniques that at least 12 % of energy can be reduced on yearly basis.
- A night-ventilated library located in Ireland is considered and analysed in Finn et al. (2007). The building is modelled using ESP-r, and the mean bias deviation between the predicted and experimental data is better than 0.45 °C for the dry bulb temperature. Examination of night ventilation rates indicated that increasing night ventilation up to 10 air changes per hour result to 1 °C reduction for medium gains and 2 °C reduction for high internal gains.

Therefore, night ventilative cooling is a very effective method to reduce the air-conditioning demand for any building type and improve thermal comfort during daytime regardless the climatic conditions.

Night ventilation is one of the most cost-effective and efficient passive cooling techniques for low-income households (Springer et al. 2005). Studies show that in hot climates, 12 ach/h during night with 1 ach during the day may provide comfortable indoor conditions (Golneshan and Yaghoubi 1990). A careful design of opening is very important for the improvement of the night ventilation effectiveness in urban regions (Geros et al. 1999; Kolokotroni 2001; Maragogiannis et al. 2011; Kolokotroni et al. 2006).

4.4.2 Ground Convective Cooling

Another convective cooling strategy is the drawing of outdoor air through tubes buried in the ground and dumped into the dwelling. Made of material that allows easy thermal transfer, these tubes are buried a few metres deep to avoid the warmer daytime surface temperatures. The designation of this system varies, as it could be referred to as “earth tubes” or as “ground-coupled air heat exchangers”.

Many applications of ground convective cooling are available around the world. Ground convective cooling has been applied in various types of buildings as listed below:

- The application of ground convective cooling in an office building in Belgium is described in Breesch et al. (2005). The building has a surface around 2000 m^2. The used earth-to-air heat exchanger includes two concrete pipes of 80 cm internal diameter and 40 m length, buried at depths 3 and 5 m respectively. Monitoring of the building has shown that the maximum supply of air from the buried pipes never exceeds 22 °C. In parallel, it is found that ground convective cooling decreases the discomfort hours in the office by 20–30 % during the whole summer period.
- The application of ground convective cooling in three office buildings in Germany is described in Pfafferott et al. (2003). During the summer period when the ambient temperature was above 30 °C, the exit temperature in the exchanger was close to 18 C. The outlet air temperature was always between 20 °C and 5 °C. The specific energy gains were calculated close to 13.5 Kwh/m^2 per year.
- Two polyethylene pipes having a length of 90 m and buried at 2.80 m depth are used to supply cooling to an office building of 1488 m^2 in Germany. The system is monitored for about 3 years, and it is found that the temperature drop in the pipes was close to 10 °C, while the COP of the system was measured between 35 and 50.
- The application of almost 28 buried pipes in a school in Italy is described in Grosso and Raimondo (2008). The pipes’ length was 70 m and was buried at 2.6 m. The building was not monitored, but simulation results show that the average cooling contribution of each pipe was close to 760 kWh/m^2 per year.
- Four ground pipes buried at 1.5 m depth are used to provide cooling to the philosophical school of the University of Ioannina, Greece. The building has a surface of 4100 m^2. The system was monitored and is found that it provides 33 kWh/m^2 per year for cooling purposes.
- The application of an earth-to-air heat exchanger to a hospital building in India is described in Badescu and Isvoranu (2011). The monitoring of the system showed that when the maximum ambient temperature was close to 42 °C, the maximum air temperature at the exit of the tubes was close to 25.5 °C
- A ground cooling system composed by buried pipes of 40 m length, buried at 4 m depth, is installed in a building named “CircoLab”, which is a multifunctional facility with corporate, conference, recreational, cultural and community functionalities. The surface of the building was 382 m^2. Monitoring

of the system has shown that the exit temperature from the buried pipes was almost 5 °C lower than the ambient temperature.

- The use of ground convective cooling in a multi-storey passive house building in Romania, (AMVIC PH), is reported in Badescu and Isvoranu (2011). The ground exchangers consisted of two parallel drums of external diameter 400 mm buried at 3.5 m depth. Monitoring showed that when the ambient temperature was 32 ° C, the temperature at the exit of the pipes was close to 26 °C.
- The application of an earth-to-air heat exchanger in a passive house in France is described in Thiers and Peuportier (2008). The pipes are buried at 1.6 m and have a length of 30 m. The system is connected to a building of 132 m^2 and was used for ventilation and cooling purposes. The project is not monitored, but simulation results show that the use of the EATHE reduces the cooling degree days from 56–22. Another application of ETAHE in residential buildings in France is described in Trombe et al. (1991). It is found that when the ambient temperature was 37 °C, the exit temperature from the exchangers was 24 °C. In parallel, the building connected to the EATHE was almost 3 °C lower temperature than the same building not associated to an exchanger.

In addition ground convective cooling for cities is proposed by various researchers. Fintikakis et al. (2011) evaluated the microclimatic modifications that were applied in the historic centre of Tirana, Albania. Among other mitigation techniques, ground convective cooling was applied. The researchers found that the maximum temperature drop due to all the applied techniques was 3 K, while the maximum contribution of the earth-to-air heat exchangers was found to be close to 0.7 K.

Ground cooling and the earth-to-air heat exchangers can be also a viable solution for low-income households. A significant number of buildings have been designed and monitored, and the performance of the system has been proven very high (Thiers and Peuportier 2008). For example, the use of earth-to-air heat exchangers in a new housing development in Portugal has contributed to a reduction in the cooling needs by 95 % compared to an air-conditioned building, though the mean cost per building was quite low, at close to 7500 €/house (Santamouris and Kolokotsa 2013).

4.5 Conclusions

In this chapter, an analysis of the convective passive cooling techniques for buildings is performed. Moreover, the applicability of those techniques in low-income households is revealed. The analysis showed that the needs for cooling will continue to increase and is expected that the situation will be deteriorated especially for low-income population.

Moreover passive convective cooling technologies have been tested in demonstration and real scale applications with excellent results. The efficiency of the proposed passive cooling systems is found to be high, while their environmental quality is excellent. Based on the research developments, many of the proposed systems and in particular the heat dissipation systems have been commercialised and are available to the public.

It is evident that further research is necessary in order to optimise the existing systems and develop new ones in order to relief the energy burden that is continuously increasing.

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